SIGNATURES OF FIREBALL FRAGMENTATION AT THE PHASE TRANSITION*

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It is explained why and how the fireball created in ultrarelativistic nuclear collisions can fragment when passing the phase transition. It can happen at the first-order phase transition but is not excluded even at high collision energies where the smooth crossover is present. Two potential observables sensitive to the appearance of fragmentation are reviewed: event-by-event changes of rapidity distributions and proton correlation in relative rapidity.

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1. Introduction

In ultrarelativistic nuclear collisions we probe bulk strongly interacting matter at extreme temperatures. The medium is hottest and densest immediately after the passage of one nucleus through the other. In collisions at highest available energies the deconfined state of colour charges is created shortly after the initial impact. Then, the subsequent expansion and cooling is rather fast. In the longitudinal direction it is described by a Hubble-like scaling flow profile. The flow velocity in transverse direction reaches about $0.7c$ at $\sqrt{s}_{NN} = 200$ GeV. The total lifetime of the hot fireball is about 10 fm/c.

If the fast evolution of the fireball includes the transition from deconfined to hadronic state we have a reason to expect non-equilibrium phenomena. I want to argue that one such scenario which could be realized is that the fireball matter violently decays into many smaller fragments or droplets [1]. In other works this process may be called cavitation or fragmentation [2].

In the next Section arguments are presented why fragmentation at the transition is a thinkable process. If it really happens, however, we ought

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to identify observables that are sensitive to it. In order to study such observables, a Monte Carlo model called DRAGON has been developed for the creation of artificial data including the effect of fragmentation. It is briefly introduced in Section 3. In Section 4 I explain two potential observables sensitive to the fragmentation scenario: event-by-event fluctuations of rapidity distributions and correlation functions in relative rapidity.

2. Fragmentation of the fireball: why and when

When bulk matter passes through a phase transition fast, this can lead to fragmentation [3, 4]. Let us first explain this on an example of a first order phase transition. For illustration, let us consider an isotherm of the van der Waals equation of state. Below the critical temperature it exhibits a wiggle which is connected with the phase transition. Maxwell rule dictates a horizontal line instead of a wiggle. This describes a *slow* evolution of the system. Along the straight line gradually larger and larger volume switches to the new phase. When isothermal expansion is *fast*, the system first keeps to the original isotherm and returns to the straight horizontal line when fluctuations initiate the phase transition. In case of a *very fast* expansion even the local minimum of the wiggle can be reached. Beyond this point the system becomes mechanically unstable and spinodal fragmentation sets in [5]. Realistic estimates show that in nuclear collisions the expansion rate may be larger than the nucleation rate for the bubbles of the new phase and the spinodal fragmentation scenario could be realistic [6].

Nevertheless, at collision energies above few tens of GeV per nucleon the baryochemical potential is so low that a first order phase transition appears highly unlikely and we rather see a smooth crossover. Spinodal fragmetnation is then irrelevant. It has been noted recently, however, that the bulk viscosity has a sharp peak at T_c as a function of temperature [7, 8, 9]. Based on this observation it has been proposed that the fireball could fragment at T_c as a consequence of the expansion flow which is established at this point already, and the sudden unwillingness of the system to change the volume, connected with the appearance of the bulk viscosity [1].

In summary, fragmentation of the fireball at T_c is a realistic scenario at any ultrarelativistic collision energy although it may be more natural to appear at higher baryochemical potential connected with first order phase transition.

3. DRAGON: the Monte Carlo model

In order to test various observables that can be sensitive to the production of hadrons from droplets a Monte Carlo model was constructed, called

DRoplet an hAdron GeneratOr for Nuclear collisions (DRAGON) [10]. The model includes two types of particle production: final state hadrons may be emitted directly from the bulk fireball or from droplets into which (part of) the fireball decayed. These two sources can be combined since even after fragmentation into smaller droplets some dilute matter may remain in the space between them. The shape and expansion pattern of the fireball from which the droplets originate are inherited from the blast wave model. Droplets obtain the velocity which is given by the local flow velocity at the position where they are produced. Their sizes can be set in the simulation. Generally, they should be given by the expansion gradients and properties of the medium. The chemical composition of the produced hadrons is determined according to equilibrium prescription. Mesons and baryons with masses up to 1.5 and 2 GeV/c^2 are included, respectively. Resonance decays are accounted for.

4. Observables sensitive to fragmentation

In general, a decay of the fireball into many droplets will be reflected in clustering in momentum distribution. Velocities of the produced hadrons will be clustered around the velocity of the droplet from which they originate. Thus we expect clustering in the momentum space. The amount by which the momenta of hadrons differ from the vector corresponding to the droplet velocity increases with growing temperature and is smaller for heavier hadrons. For pions, however, clusters are well visible in the momentum space if the temperature is unrealistically low, e.g. 10 MeV. For realistic freeze-out temperature the momenta are smeared. Clustering is more pronounced, however, for heavier particles.

In the following we mention two potential candidate observables for the identification of clustering in momentum space that could be due to droplets.

4.1. Fluctuations of rapidity distributions

Suppose we select very narrow centrality class and consider a group of events with initial conditions as close to each other as possible. In such a case one might expect the same scenario running in each event. If the fireball stays in one piece, we would then expect that the spectra of final state hadrons will be identical within statistical uncertainties. Not so, however, in the case of fireball fragmentation. In this case, droplets will be produced in different places in each event and consequently the momentum clusters will also differ event by event. We further focus on rapidity distributions. The statement is that in case of fragmentation there will be non-statistical differences between rapidity spectra measured individually in each event.
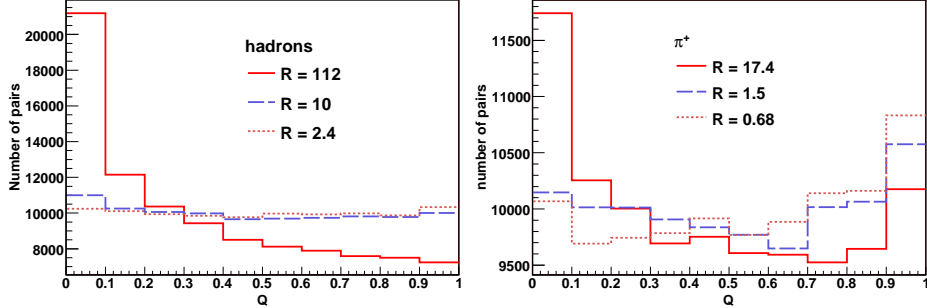
Fig. 1. The Q-histograms evaluated on 10^5 event pairs taken from samples of 10^4 events. The red solid line shows the histogram from events with droplet production. The dashed and dotted lines show results from simulations with only bulk production assumed from $\sqrt{s_{NN}} = 130$ GeV and 9 GeV, respectively. Left panel: all charged hadrons, right panel: only positive pions. R gives the statistical significance of the peak at $Q = 0$.

The statistical tool which can be used for identification of such a situation is the Kolmogorov-Smirnov test [11, 12, 13]. It defines the measure of "unlikeness" of two empirical distributions, which in our case will be two samples of measured hadron rapidities from one event. For a pair of events a quantity Q is defined. It is the conditional probability that two events will look more differently, provided they are generated from the same probability distribution. It is constructed so that a sample of events with common underlying probability (e.g. rapidity) density will produce a flat histogram of Q's, if Q is measured in a large number of *event pairs*. If within a set of events we obtain too many Q values close to 0, then this means that the events are not drawn independently from the same probability distribution.

We have simulated sets of events with DRAGON. In order to judge on the effect of fragmentation we investigated events where all hadrons have been emitted from droplets. The average size of droplets was 5 fm^3. For comparison, other sets of data were simulated where no droplets have been taken into account. Chemical composition was tuned as to correspond to that at $\sqrt{s_{NN}} = 130$ GeV and the rapidity distribution of hadrons or droplets was uniform. One simulation without droplets was performed with Gaussian rapidity distribution and chemical composition from collisions at $\sqrt{s_{NN}} = 9$ GeV (FAIR energy). In Figure 1 we clearly see that the presence of droplets leads to a pronounced peak at low Q. In charged hadrons there is a small peak also in case with no droplets. This is due to resonance decays which act like very small droplets: they correlate two or three final state hadrons. To get rid of them one can use only pions or only protons for the measurement. On the other hand, that decreases the statistics and
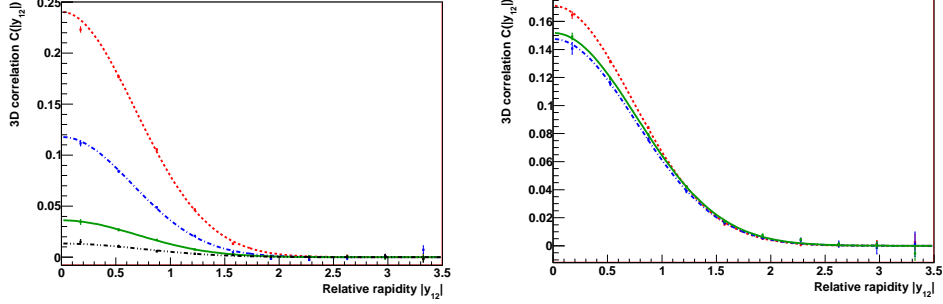
Fig. 2. Correlation functions of protons in relative rapidity calculated for a situation in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. Left panel: one half of hadrons is produced from droplets, their average sizes are $5\,\mathrm{fm}^3$ (black dash-dot-dotted curve), $10\,\mathrm{fm}^3$ (green solid), $25\,\mathrm{fm}^3$ (blue dash-dotted), and $50\,\mathrm{fm}^3$ (red dotted). Right panel: the influence of resonance decays on the correlation function. All particles form droplets with average size $25\,\mathrm{fm}^3$. Correlation function with all resonance decays included (red dotted), simulation with no resonance production included (green solid), simulation with resonances included but protons from decays of Δ resonances not taken into analysis (blue dash-dotted).

has an impact on the method, which is, strictly speaking, so far only well constructed in the limit of very large multiplicity.

4.2. Proton rapidity correlations

Two hadrons steming from the same droplet will have similar rapidities. Thus we expect non-trivial correlation function in case of fragmentation. The hadron rapidities will differ from the rapidity of the droplet by thermal component of the velocity. Thermal motion is slower for heavier particles. Thus it is reasonable to choose heavy particles. Since the abundance of hadrons of given kind decreases with increasing mass, we have to find a balance between small thermal smearing and large statistics. Protons appear as a good choice [14, 15].

On DRAGON-generated events we have studied proton correlations in *relative rapidity* defined as $y_{12} = \ln[\gamma_{12} + \sqrt{\gamma_{12}^2 - 1}]$ where $\gamma_{12} = \frac{p_1 \cdot p_2}{m_1 m_2}$ [16]. We found that the correlation function is measurably non-zero for droplets with average volume as small as $5\ \mathrm{fm}^3$ and also if only a part of the hadrons comes from the droplets and the rest is from the bulk in between. Surprisingly, we observed that resonances which decay into protons make the proton correlation function even more pronounced (Figure 2). This is due to their higher mass resulting in weaker thermal smearing.

5. Conclusions

We have presented two possible observables which could help to indicate fragmentation of the fireball in ultrarelativistic nuclear collisions: event-by-event changes of the rapidity distributions identified via Kolmogorov-Smirnov test and correlation of protons in relative rapidity. Among other observables which are worth investigating there are imaging, elliptic flow and its fluctuations, correlations in rapidity and azimuthal angle, etc. We plan to address these topics in the near future.

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